A Precision Micro-Positioning System by Using Hinge Mechanism

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Abstract: A precision micro-positioning system with a high displacement resolution and wide motion range has been required for industrialized applications in variety fields. This paper discusses the design of a precision micro-rotation stage with flexure hinges. Proposed system is applied to grinding machine for micro parts. Rotational motion is generated with this system. For this systems having a full rotation motion with high precision, a dual servo system with a coarse stage and a fine stage is proposed.

Keywords: Flexure hinge, Rotation motion, Dual servo, Micro motion, Monolithic structure.

1. INTRODUCTION

High precision positioning is an important issue in the fields of manufacturing, assembly and measurement. Recently, high precision device is needed in field of optical instrument, semiconductor manufacturing line, precision machine tools, and bio-engineering.

It is difficult to satisfy high precision and large motion range simultaneously. Dual servo mechanism has been used for such cases. It is constructed with fine motion mechanism and coarse one. So the dual servo system contains two actuators that act in serial or parallel. One is the fine actuator that covers the short moving-range of sub-micrometer accuracy and high bandwidth. The other is the coarse actuator that is low bandwidth and large stroke. These actuators serve each other; so dual servo system can get both high precision and large stroke.[4]

Heuijae pahk et al developed ultra precision positioning system for servo motor-piezo actuator using the dual servo loop and digital filter. Lichuan Li proposed the dual system for cooper loss reduction of a VCM using an auxiliary rotary motor. Gweon et al proposed the micro stage for 3DOF motion with VCM and hinge mechanism.[1-3]

In this paper, we developed the high precision positioning system for grinding machine. The quality of a precision product depended on the accuracy and precision of its manufacturing process. The Developed system supply the high precision and full rotation motion range.

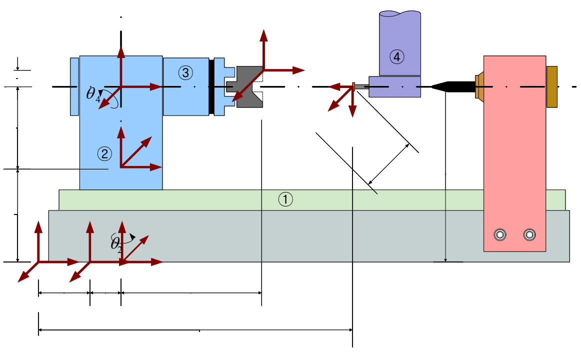


Fig. 1 Schematic picture of special grinding machine

Proposed rotation module is applied to grinding the micro pin or tool. Material is rotated for grinding process to desired angle with proposed rotation module in this paper. Fig.2 show the grinding process.

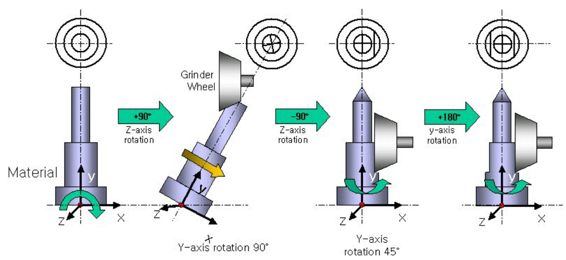


Fig.2 Manufacturing process with rotation module

Flexure hinge is used in fine motion mechanism, Flexure hinge is used to enhance the precise movement and flexure mechanism is produced from a single monolithic solid. In most cases, a flexure hinge has also been used as a smooth guide for the lever system, because it has many advantages such as good linearity, no friction, small hysterics and a simple structure.

2. MECHANISM DESIGN

2.1 Flexure hinge element design

Flexure elements almost invariable consist of either leaf springs (rectangular hinge), notch hinges or elliptic cross section. Each hinge is applied to engineer part and is utilized by its property. Rectangular hinges has largest displacement and right circle hinges has more accurate than hinge which its length is same other. Elliptic cross section hinges is related to the ratio, ε, of the major to minor axes of the ellipse which ranges from 1 for a circular notch to infinity for a leaf type spring. The leaf springs typically consist of a slender member connected at each end by two rigid bodies to provide a compliant coupling and the notch hinge has been traditionally produced by drilling and reaming (or jig-boring) two closely spaced holes to produce the hinge11). The right circle hinge is used in this mechanism, and It's modeled as figure No.5.[11]

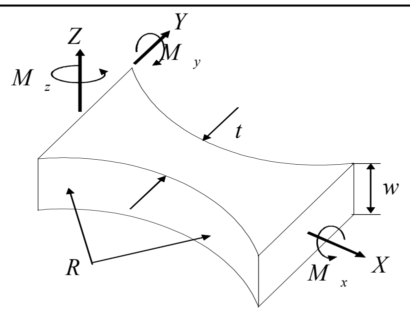


Fig.3 Flexure hinges model of right corner type

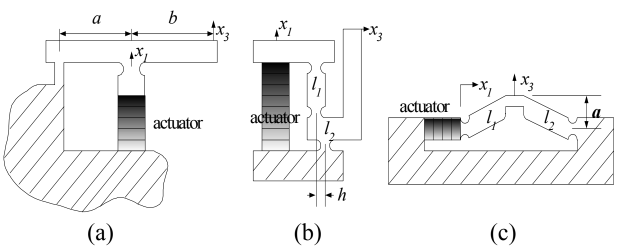
Based on the suggested model, a Newtonian method is used to derive the equation of motion. Paros and Weisbord have given an analytical solution for the bending stiffness of a right circle hinge. In this study, the following equations are used by

$$k_{\theta_z M_z} = \frac{2Ewt^{5/2}}{9\pi R^{1/2}} \qquad (1)$$

2.2 Amplifying mechanism

Fig. 2 shows three types of amplifying mechanisms. Micro motion actuator has small moving range, so it need to amplify the moving range. Amplified mechanism with flexure hinge satisfy this propose. This mechanism has not backlash and error of assembling. Fig. 2(a) is a conventional lever mechanism and an equivalent mechanism with Fig. 3(c). In Fig. 3(c), the lever ratio can be envisaged as that due to the rotation of an arm fixed to the pivot due to the forces from another free arm connected at some angle. It is obvious that the output displacement is due to the motion of the midpoint necessary as the spacing between opposite ends of the two rods changes. Fig.3 (a) is the direct lever type, Fig.3(b) is indirect lever for linear or angular output amplification, and Fig.3(c) is the indirect, two-bar lever for linear amplification. The amplification ratio of (c) is such as eq.1 (Fig. 3(c))[11]

$$\frac{x_3}{x_1} = \frac{1}{\sin\theta_1} \qquad l_1 \sin\theta_1 = a \qquad (2)$$



(a) (b) (c)

Fig. 4 Amplify mechanism with flexure hinge

The amplification is dependent upon ratio of l_1, l_2 is shown in Fig. 9. Two bar lever using two links increases or decreases amplification of either input displacement or force by ratio of l_1, l_2. When x_1 input variable works, b which is the base line's length can represent α, β. That output x_3 is equaled to c-a for input x_1 is shown in Fig. 4

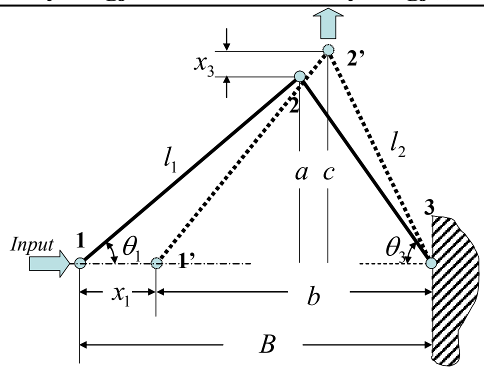


Fig.5 Amplify mechanism model

$$x_3 = c - a \qquad (3)$$

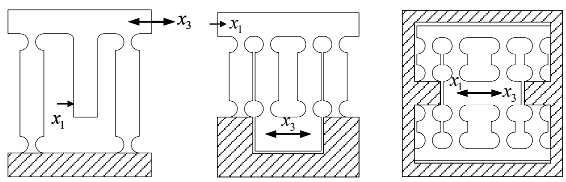
$$b = l_1 \cos\theta_1 + l_2 \cos\theta_3 - x_1 \qquad (4)$$

$$c = \frac{1}{2b}\sqrt{(l_1+l_2+b)(l_1+l_2-b)(l_1-l_2+b)(-l_1+l_2+b)} \qquad (5)$$

$$a = \frac{1}{2b}\sqrt{(l_1+l_2+B)(l_1+l_2-B)(l_1-l_2+B)(-l_1+l_2+B)} \qquad (6)$$

2.3 Translation mechanism

It is various that elements go on linear guide. However typically it is four bar link with flexure hinges. Four bar link with flexure hinges divide into three classes as Fig. 4. Fig. 4(a) is typically element of linear guide and the larger stiffness. Fig. 4(b), (c) has the compound rectilinear spring. Particularly Fig. 4(c) is used to state which exist unbalanced temperature which is composed of symmetric structure. In this paper, we used the first type, it's simple structure, so we can design the mechanism to be small size, and manufacture it easy



(a) (b) (c)

Fig.6 Translation mechanisms with flexure hinges

The stiffness and frequency of rotation body is dependent upon the property of hinge and natural frequency of mechanism system, we can derive the natural frequency with hinge stiffness model. Fig.7 show the translation mechanism model and design parameter.

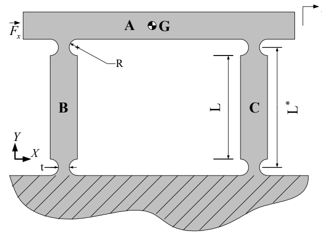


Fig.7 Translation mechanism model and parameter

Where θ_z is angle of link B, C. M_A is mass of link A, I_c is inertia of link B, C , L^* is length of link to base rotational point from upper rotational point, M_C is mass of link B, C.

$$\theta_z = \sin\left(\frac{x}{L^*}\right) \approx \frac{x}{L^*} \qquad (7)$$

Kinetic, Potential energy can present to (8), (9) using (7).

$$T = \frac{1}{2}M_A\dot{x}^2 + 2\left(\frac{1}{2}I_c\left(\frac{\dot{x}}{L^*}\right)^2\right) \qquad (8)$$

$$V = 4\left(\frac{k_{\theta_z M_z}\theta_z^{\,2}}{2}\right) \approx 2k_{\theta_z M_z}\left(\frac{x}{L^*}\right)^2 \qquad (9)$$

by Lagrange's equation :

$$\left(M_A + \frac{2I_c}{L^{*2}}\right)\ddot{x} + \left(4\frac{k_{\theta_z M_z}}{L^{*2}}\right)x = F_x \qquad (10)$$

Natural frequency is ;

$$\omega_n = \sqrt{\frac{k_{\theta_z M_z}}{M_A L^{*2} + 3M_C L^2\left(\frac{1}{3} + \left(\frac{R}{L} + 4\frac{R^2}{L^2}\right)\right)}} \qquad (11)$$

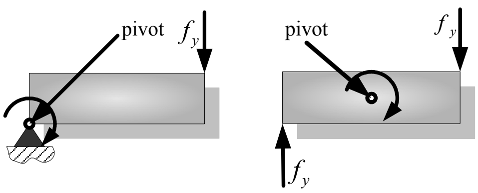
The total 'static' linear stiffness of the flexure can be obtained when the acceleration is to be zero, and is :

$$\frac{F_x}{x} = \frac{4k_{\theta_z M_z}}{L^{*2}} \qquad (11)$$

3. ROTATION MOTION MODEL

3.1 Motion mechanism

A dipole force generates rotational motion. The basic structure of one-axis motion with dipole force is shown in Fig. 8. Fig.8(a) shows that reaction force is generated by dipole force and Fig.8(b) shows that rotation motion of body is made with sum of two forces which have same scale and different direction.



(a) (b)

Fig. 8 Rotation motion model

If a force scale of two forces were different, a rotation center will be changed from ideal pivot point as Fig. 8. ; we can derive the rotation center error in this figure. It is difficult for real system to make the two forces that have same scale. It has always the error of pivot point from ideal one by driving forces. Therefore rotation body need a guide structure. This mechanism use a bearing and shaft that is connected to base structure.

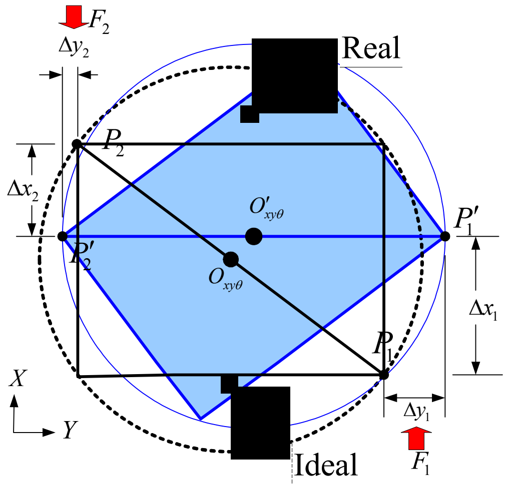


Fig.9 Rotation motion model and moving pivot point

3.2 Mechanism structure

Fig.8 shows the schematic of mechanism structure. This is half model of proposed rotation module. It is consisted with three parts; a linear guide part, a amplify part(two bar lever) and a rotation body.

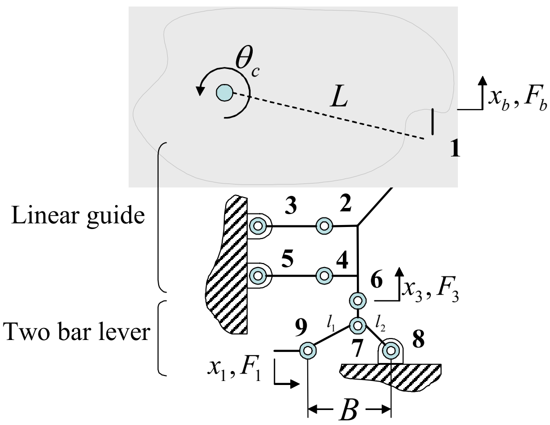


Fig.10 Motion mechanism model

Eq.(12) is constrain of moving body.

$$L\sin\theta_c = x_3 \qquad (12)$$

$$\theta_c = \sin^{-1}\left(\frac{x_3}{L}\right) \qquad (13)$$

$$x_3 = \frac{1}{2b}\sqrt{(l_1+l_2+b)(l_1+l_2-b)(l_1-l_2+b)(-l_1+l_2+b)} - \frac{1}{2B}\sqrt{(l_1+l_2+B)(l_1+l_2-B)(l_1-l_2+B)(-l_1+l_2+B)} \qquad (14)$$

where $b = l_1\cos\alpha + l_2\cos\beta$

3.3 FEM analysis and simulation

Motion range and mechanism is verified with FEM analysis and model simulation. Fig. 11 is cad model of rotation module. We can see the rotation center and mechanism behavior in Fig.12.

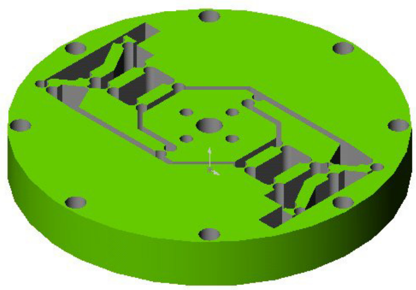


Fig.10 Micro motion mechanism CAD model

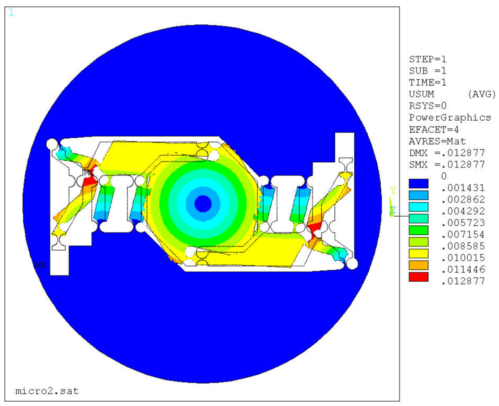


Fig.11 Analysis result with FEM [displacement]

In Fig.11, a circle shape is shown, it display the rotation center point. Graph Fig.12.shows the ratio of input and output displacement angle.

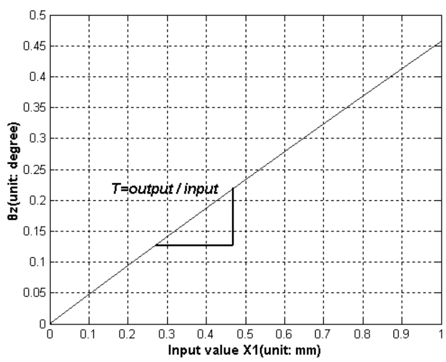


Fig.12 The ratio of input and output

When a input motion is applied as 1mm, rotation body is rotated 0.46 degree. We can get desired angle of rotation. Eq.15 is a mechanical advantage function of micro rotation module

$$T = \frac{\sin^{-1}\left(\frac{(c-a)}{L}\right)}{x_1} \quad (15)$$

Input resolution is 0.001mm, so a rotational resolution of this mechanism is 0.00046 degree. It is measured with encoder at a end-stage that a chuck is attached.

4. DUAL SERVO SYSTEM

4.1 System control strategy

The proposed system is a dual servo mechanism. The macro motion is generated with servo motor. A rotation angle is measured by a rotational linear encoder. The rotational linear encode is located at end part of system. So it can measured rotation angle that is a total of micro and macro rotation moving angle. The macro stage is controlled until the angle error is less than 0.001 degree. After the controlling of the macro stage, the micro stage will be controlled. The encoder resolution is 0.0001 degree. We use a PID controller for controlling macro and micro stage. Fig.13 shows the procedure of control.

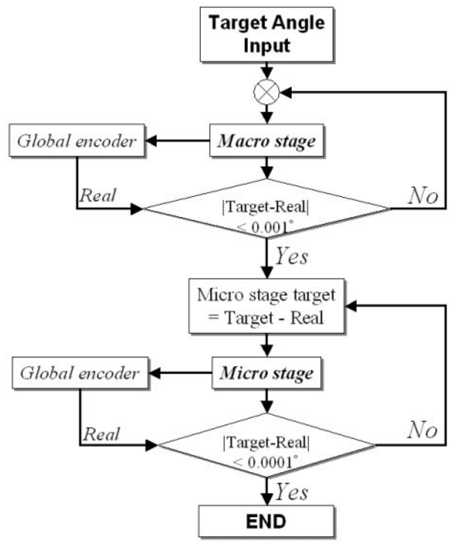


Fig. 13 Flowchart of a control strategy

4.2 Experiment system

When material is processed with grinding machine, the reaction force from grinding wheel and material is so high. So rotation stage is deflected with this force. In this paper, we use the brake-clutch module. During the grinding work, brake module fix the rotation stage. So we can prevent the deflection. Fig.14 shows the experiment system and Fig.15 is CAD model of system.

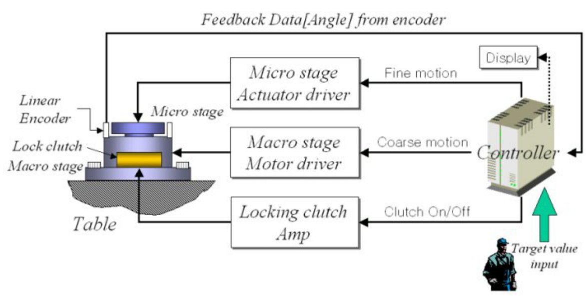


Fig. 14 Experiment system schematic

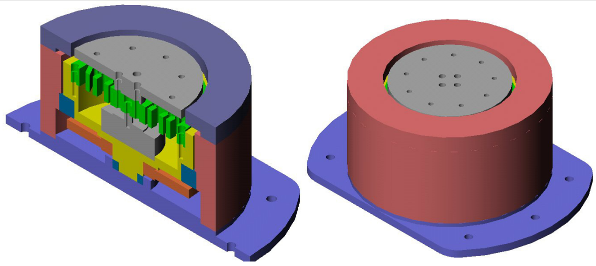


Fig. 15 High precision rotation module

5. CONCLUSION

We proposed a high precision rotation system. It is consisted with the micro and macro parts. The micro motion mechanism is designed with flexure hinge mechanism.

Flexure hinge mechanism for a micro rotation stage is designed and verified with FEM. The transfer function and natural frequency is derived. This mechanism has a 1degree motion range.

The proposed mechanism has the high resolution about 0.0005 degree. The dual servo system is useful for a large motion range and high precision

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